ANNALI DI GEOFISICA, VOL. 44, N. 3, June 2001

Pangea B: an artifact of incorrect paleomagnetic assumptions?

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Abstract
The detailed plate reconstruction within Pangea megacontinent has been an ongoing debate among the paleomagnetic community for decades. The Pangea B hypothesis, implying a 3500 km Triassic dextral megashear on the Gondwana-Laurussia limit, has been recently reinforced by new data, excluding Southern Alps sites. This configuration, at odds with geological evidence, does improve the coherency of paleomagnetic poles from Gondwana and Laurussia. However, the corresponding apparent latitudinal difference between the two supercontinents can be easily accounted for, without invoking this megashear, considering the effect of inclination error (or equivalent non-dipole field) on the site distribution used in the paleomagnetic study. Once northern hemisphere Southern Alps data are considered, Pangea B no longer holds. Large inclination errors (10°-30°) are to be expected in the Permo-Triassic continental sediments as demonstrated in the Esterel and possibly Argentina Permo-Triassic studies or in Neogene analogues such as the Siwalik or Catalan basin sequences. An overall discussion of the inclination error problem is given. Analysis of the database also suggests an age bias between the Gondwana and Laurussia reference poles at the Permo-Triassic boundary, partly responsible also for the latitudinal shift. Finally, Moroccan data are demonstrated to be irrelevant for computing a Gondwana early Triassic pole.

Key words *paleomagnetism – Trias – Permian – Pangea – inclination error*

1. Introduction

The major postulates of paleomagnetism applied to tectonics are:

1) Characteristic natural Remanent Magnetization (ChRM) is parallel to the geomagnetic field in which it is acquired.

2) This field when average through time corresponds to a geocentric axial dipole (GAD hypothesis).

3) ChRM acquisition can be precisely dated, and often equated to the age of rock formation.

Application of these simple rules, through the compilation of paleomagnetic poles and apparent polar wander paths for major plates, has provided major constraints on geodynamic reconstructions (Van der Voo, 1993). However, these postulates are only valid to a certain debatable extent. Failure of the first one has been clearly demonstrated in the case of the inclination error of sediments, with errors up to 30°, increasing with the anisotropy of the rock (*e.g.*, Tauxe and Kent, 1984; Collombat *et al.*, 1993 and references of chapter 2). The GAD hypothesis is valid with a 5% error for the last 5 Myr (Quideleur *et al.*, 1994), and there is significant evidence for a large non-dipole field (NDF) of 15 to 25% in the past (Schneider and Kent, 1990; Kent and Smethurst, 1998; Rochette *et al.*, 1998). Finally, determination of the ChRM age

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is subjected to several uncertainties. Not even considering the problem of eventual remagnetization, the age initially assigned to a rock unit may have been changed thirty years after the original paleomagnetic study. Reassessment of earlier radiometric or biostratigraphic dates often fails to be recorded in the paleomagnetic database, whose bulk data on the major continents often date back more than 25 years. The purpose of the present review paper is to illustrate how these considerations affect the Pangea B hypothesis (Irving, 1977).

The configuration of the megacontinent Pangea prior to its splitting in early Jurassic times is well constrained by plate tectonic models based on oceanic floor spreading. The persistence of this configuration (called A1) through the whole duration of Pangea, *i.e.* since late Carboniferous Hercynian orogenies, is a matter of debate among paleomagnetists and mainly concerns the respective position of Gondwana and Laurussia (Smith and Livermore, 1991; Van der Voo, 1993). The mean paleopoles of these two parts of Pangea steadily disagree during the existence of Pangea, but the early and late poles of this set can be fitted using another configuration called A2. A2 configuration implies a counterclockwise relative rotation (during A2 to A1 change) of 20° of Gondwana with respect to Laurussia, without many relative displacements and overlaps along the contact of North America and North-West Africa. After this fit, the Permian and early to middle Triassic poles still disagree by an angle β, in between 10° and 20° (Van de Voo, 1993). Only a latitudinal movement of Africa with respect to Laurussia of the same

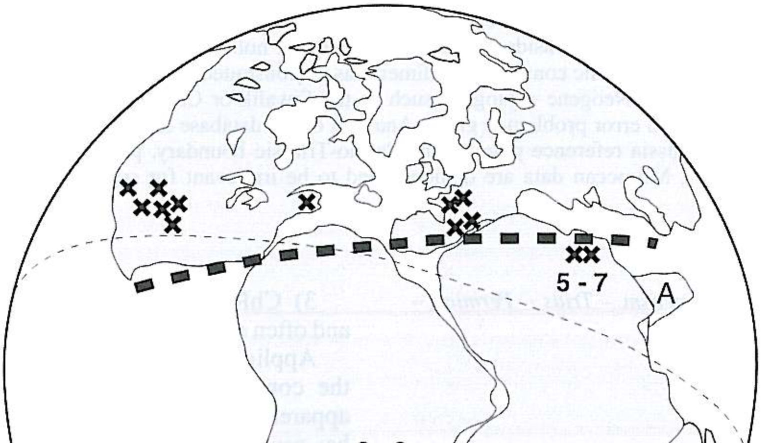

Fig. 1. Reconstruction of Gondwana and Laurussia late Permian-early Triassic position in the Pangea B configuration after Torcq *et al.* (1997), including Apulia (A). Sites used in this study for mean pole calculations are indicated by crosses (numbers refer to table I).

amount β can resolve this disagreement. This requires a dextral «megashear» along their contact (fig. 1). The Pangea B reconstruction (Irving, 1977; Hallam, 1983) corresponds to a 3500 km displacement during the end of the Trias, *i.e.* at a rate of the order of 10 cm/yr. Following Van der Voo (1993) this reconstruction appears geologically unrealistic for two major reasons:

– Such a megashear, unique in geological history for continental plates, should have resulted in tremendous mountain building and basin formation due to the non-linearity of the fault zone.

– The Appalachian-Mauritanides late Hercynian suturing, which is quite well constrained by the paleogeographic and tectonic synthesis (Lefort and Van der Voo, 1981; Vauchez *et al.*, 1987) would be either rejected in favor of a Appalachian-South America and Mauritanides-Hercynian Europe suturing poorly constrained by geological evidence, or achieved by a sinistral megashear, even more unrealistic. This back and forth movement between B and A2 configurations is also suggested by the late Carboniferous paleopoles.

A qualitative argument in favor of Pangea B, the existence of dextral movements and transtension basins in Southern Europe and North West America during the Permo-Triassic period (Arthaud and Matte, 1977), is also accounted for by the A2 to A1 rotation. This latter model implies a much more realistic displacement in between 150 and 300 km.

Therefore, it was concluded that the discrepancy of Permo-Triassic mean paleopoles in the A2 configuration is the result of poor number and quality of the data, together with problems in age control and ultimately in the GAD hypothesis (Smith and Livermore, 1991; Van der Voo, 1993). Moreover, plate reconstruction within Gondwana is itself inconsistent with paleomagnetic results, suggesting that only W Gondwana (Africa and South America) should be compared to Laurussia. This selection implies a dramatic decrease of Gondwana poles to be used in the reconstruction, further questioning the significance of β values.

Recently, two attempts to refine the W Gondwana APWP in Permian and Triassic times have led to contradictory results. Using a majority of Southern Alps sites, Muttoni *et al.* (1996) concluded that the preferred reconstructions should be Pangea A2 in middle to late Triassic and

Table I. W Gondwana late Permian - early Triassic results, selected in Torcq *et al.* (1997). Studies where inclination only is used in mean Gondwana pole indicated by a star. Numbers as in fig.1. Full references in Torcq *et al.* (1997). Inclination of ChRM in stratigraphic coordinates together with latitude error according to model with $f = 0.5$.

Number	Unit	Rock type	Inclination	Error lat.	Reference
1	Sudair Shale, Arabia	Red beds	– 22	11	Torcq *et al.* (1997)
2	Sakamena Fm., Madagascar	Red beds	– 50	19	McElhinny (1976)
3*	Tanzania	Red beds	– 58	19	Nyblade *et al.* (1993)
4	Cassanje series, Angola	Red beds	– 41	18	Valencio *et al.* (1978)
5*	Ait-Adel, Morroco	Dolerite sill	43	0	Hailwood (1975)
6*	Issaldin, Morroco	Dolerite sill	35	0	Hailwood (1975)
7*	Morroco combined	Sed. and volc.	45	–	Daly and Pozzi (1976)
8	Corumbatai Fm, Brazil	Red beds	– 45	18	Valencio *et al.* (1976)
9	Irati Fm, Brazil,	Marls and limestones	– 38	17	Pascholati *et al.*(1976)
10	Amana Fm., Argentina	Red beds	– 56	19	Valencio *et al.* (1977)
11	South Nihuil lavas, Argentina	Various extrusives	– 62	0	Creer *et al.* (1970)
12	Amana Fm., Argentina	Red beds	– 40	17	Creer *et al.* (1970)
13	Rio Chasquil, Argentina	Red beds	– 44	18	Thompson (1972)

Pangea B in early Permian, with no preference for late Permian - early Triassic times. The resulting β angles are near 10° or less. However, the improvement brought by Pangea B for early Permian is hardly significant: β of 5° ± 6° instead of 9° ± 6°.

Torcq *et al.* (1997) excluded Southern Alps data, based on suspicion on the actual fit between Apulia and Africa. Using new data from Arabia, Africa and South America they proposed a rather well defined late Permian early Triassic pole (244 ± 11 Ma) for W Gondwana (see table I) which again favored the Pangea B hypothesis. The updated Laurussia and W Gondwana mean paleopoles from this study confirm a significant β angle of 20° ± 8°. Considering this new evidence, the Pangea B hypothesis can only be rejected by dismissing the GAD hypothesis or by invoking a persistent age bias. Indeed, the younger the Laurussia pole is compared to the (244 Ma) W Gondwana pole, the smaller the angle β.

2. Effect of inclination error and NDF on mean Gondwana and Laurussia poles

The two above mentioned possible biases on the data used by Torcq *et al.* (1997) can be considered in the light of the late Permian Esterel data (Zijderveld, 1975). These data, included in the Laurussia database, were recently reassessed (Rochette *et al.*, 1997; Vlag *et al.*, 1997) confirming the high quality of the mean poles derived from 12 volcanic units (with a total of 35 sites, 400 samples and positive fold test) and interbedded sedimentary formations (57 samples). These high quality data are clear evidence of an inclination bias of the ChRM recorded in sediments with respect to the «true» field direction recorded in volcanic rocks. Indeed, after bedding correction the volcanic formations yield a ChRM inclination of 23° ± 2° whereas for the interbedded sediments they yield 11° ± 2°, consistent with several other studies of late Permian sediments in Southern France (Van der Voo, 1993). This inclination error is responsible for a paleolatitudinal error $\Delta\lambda$ of 5° ± 2°. Interestingly the Esterel case is repeated in the Argentinian data (table I): the only volcanic pole from South America (item 11 in table I) gives a much higher inclination than the contemporary redbeds (items 10, 12-13 in table I). However the Nihuil volcanics are found further south of the other studies (300 km; this latitude difference is taken into account in fig. 2) so that the synchronism with the sediments is less well constrained than in Esterel.

Inclination error arises when anisometric remanence bearing particles are oriented within the bedding plane as a result of either deposition (case of DRM) or compaction (case of pDRM). It appears particularly common and large (of the order of 10° to 40°, see Tauxe and Kent, 1984; Collombat *et al.*, 1993; Garces *et al.*, 1996; Rösler *et al.*, 1997) in terrestrial sediments (flysch, argillites and argillaceous sandstones), because they lack bioturbation observed in most marine sediments and because the coarse grain size and large sedimentation rate favor anisotropy and DRM preservation. The effect of compaction (Anson and Kodama, 1987; Arason and Levi, 1990; Kodama and Sun, 1992; Hodych

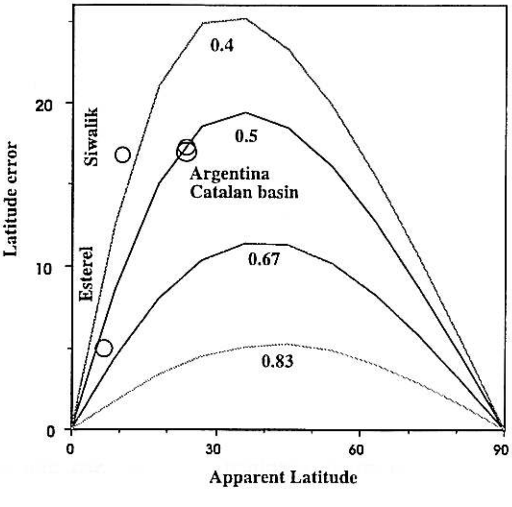

Fig. 2. Mean formation latitude error *versus* apparent latitude (from ChRM inclination) for various ChRM anisotropy coefficients *f*. Results from Esterel and Argentina (Creer *et al.*, 1970, number 11 and 12 in table I) according to the difference between volcanics and redbeds; for Siwalik and Catalan Neogene sediments predicted latitude is used.

and Bijaskana, 1993) is responsible for smaller inclination error (of the order of 5°-15°) in bioturbated fine-grained sediments where a post deposition randomization of magnetic grains occurs. A specific case may correspond to redbeds, where a chemical remanence (CRM) is often advocated (but see Kruiver *et al.*, 2000, for DRM evidence in Permian redbeds). The growth of magnetic grains, although it postdates deposition, may mimic the strong fabric of primary detrital grains resulting in an anisotropic CRM. Indeed inclination error would adequately explain the systematic too southern paleolatitudes found in Central Asia and China Cretaceous and Tertiary redbeds (Chauvin *et al.*, 1996; Kodama and Tan, 1997; Cogné *et al.*, 1999). Moreover, compaction adds to deposition anisotropy. It is therefore much more probable that a large inclination error is quite systematic in the Permian and Triassic continental sediments used in Pangea paleomagnetic reconstruction.

Inclination error (field minus ChRM inclination), which is equivalent to an octupole term in the non-dipole field, follows the simple function

$$f\,\mathrm{tg}I_F = \mathrm{tg}I_{\mathrm{ChRM}}$$

where *f* is an anisotropy coefficient (Coe *et al.*, 1985; Jackson *et al.*, 1991). Various approaches to estimate *f*, in particular from remanence anisotropy measurements, have been proposed in the above-mentioned papers. However, as no anisotropy data is presented here on the formations used for Pangea discussion, *f* will be estimated from case studies where I_F can be constrained. The above function can be translated into a latitude error *versus* latitude law (fig. 2) showing that the error is maximal at midlatitudes. Taking $f = 0.5$, *i.e.* in between the values derived from Esterel, Argentina, Catalan and Siwalik redbeds data, gives a $\Delta\lambda$ in between 15° and 20° for apparent latitudes between 17° and 48°, or real latitudes between 32° and 63°. Considering the Siwalik case (Rösler *et al.*, 1997), even lower latitude sites can yield high $\Delta\lambda s$. The geographic location of the sites integrated in the compilation of Torcq *et al.* (1997) indicates that all Laurussia poles come from apparent paleolatitudes between 0° and 15°N, while all W Gondwana sites, except Morocco, come from apparent paleolatitudes between 11°S and 45°S (table I and fig. 1). Applying an *f* value of 0.5 leads to a range of apparent latitude error $\Delta\lambda$ of 0°-13° and 11°-20° for continental sediments of Laurussia and Gondwana (except Morocco), respectively. Of the 13 poles or small circles used in Torcq *et al.* (1997) for the Gondwana mean pole, only 4 are from volcanic rocks (among which 3 are from Morroco, table I) the rest being continental sediments, with a dominance of redbeds. The situation is similar for Laurussia, with only 3 poles from volcanic rocks from a total of 19. Therefore the effect of inclination error will be only slightly reduced by the volcanic data.

The fact that the sites of each part of Pangea are situated in different hemispheres (fig. 1) entails that an inclination error would bring both Laurussia and Gondwana closer to the equator, *i.e.* in Pangea B configuration. This effect is hardly averaged out in the process of compiling a mean paleopole for each block, as the paleolongitude coverage of the sites is only about 65° for Laurussia and Gondwana. The Gondwana figure is reduced to 45° if the Arabian data of Torcq *et al.* (1997) are removed. As these data are not used in the mean as a pole but as a small circle due to their lack of declination, they have less weight in constraining the mean Gondwana pole. Considering this site distribution, the β value of 20 is therefore easily accounted for by an anisotropy coefficient *f* similar to that of the Esterel or Argentina documented cases. This latitude error will primarily contaminate the Gondwana data as they come from a higher latitudinal band than the Laurussia data. Table I shows that an average latitude error of at least 15° is predicted for Gondwana, while Laurussia could provide the remaining 5° (Esterel value). The reason for the restriction of this large inclination error effect to the period of the Permian and early Triassic is double: before and after (i) the mean poles are derived mainly from marine sediments and volcanic rocks and (ii) the hemispheric splitting is no longer valid.

Kent and Smethurst (1998), by compiling all paleomagnetic data from the Paleozoic, found that the data set was biased toward low latitude sites. The observed bias could be accounted for by an inclination error with an *f* value of 0.5.

However, as magmatic rocks in their database share a similar bias, they excluded an inclination error and invoked a large NDF, namely an octupole contribution of 25%. In fact, inclination error and octupole field produce exactly the same latitudinal error distribution (fig. 2). Unfortunately, their method requires too many sites, randomly distributed, to apply it to only Permo-Triassic data. It is therefore possible but not demonstrated by their study that this period is also affected by significant NDF, biasing paleolatitude in the same sense as discussed for the inclination error.

3. Moroccan data

The case of Moroccan data needs to be discussed separately, as it is an exception to the hemispheric splitting of Gondwana and Laurussia data. Indeed following Torcq *et al.* (1997) and fig. 1, in the Pangea B configuration the Moroccan sites at the Permo-Triassic boundary should be at about 15°N-20°N, some 5°-10° north of Southern France sites (Esterel). In the Pangea A configuration they should be equatorial, keeping Laurussia fixed. The individual paleolatitudes deduced from the three Moroccan entries used in Torcq *et al.* (1997) are in between 19°N and 26°N, apparently coherent with the Pangea B prediction. However, the ages of these poles are actually closer to the late Trias-Lias boundary (208 Ma), using K/Ar data from the source articles (Hailwood, 1975; Daly and Pozzi, 1976; Martin *et al.*, 1978; Westphal *et al.*, 1979) so that their inclusion in Gondwana mean 244 Ma pole, is quite questionable. In fact, more recent Ar/Ar ages confirm an early Liassic age at 200 ± 2 Ma (Sebai *et al.*, 1991). Moreover, the more than 50 late Trias-Lias sites studied in volcanic and sedimentary rocks (Hailwood, 1975; Daly and Pozzi, 1976; Martin *et al.*, 1978; Westphal *et al.*, 1979) in various places of Morocco have all revealed normal polarities (except the poorly defined Tichka sandstone result from Hailwood, 1975) with mean paleolatitudes around 20-25N, indistinguishable from that of Cenomanian paleopoles (fig. 3). Several reversals per Myr are observed around 200 Ma (Yang *et al.*, 1996) thus implying that all the basalts and related sedimentary rocks, if carrying their primary magnetization, should have been emplaced in a very short time. This may be the case for the basalts (Marzoli *et al.*, 1999), but it is unlikely for the sedimentary rocks. Therefore, all late Trias-Lias directions from Morocco might correspond to a remagnetization during the long normal Cretaceous period. This would fit with the Jurassic results (Hailwood, 1975; Martin *et al.*, 1978), which show lower paleolatitudes than those of Trias-Lias data. Source papers do not provide the information necessary to evaluate the fold test results. Even if that fold test were positive, it would not exclude a prefolding remagnetization as folding in Morocco postdates the mid-Cretaceous.

For Northern Africa only two results can be assigned to the Permo-Triassic age range (Abou-Deeb and Tarling, 1984). Sedimentary rocks from Tunisia and Algeria yield paleolatitudes of 7°S ± 11° and 0° ± 15°, respectively. Despite this poor precision, this does not support a position north of Southern France (11°N according to the Esterel data). Good quality early Per-

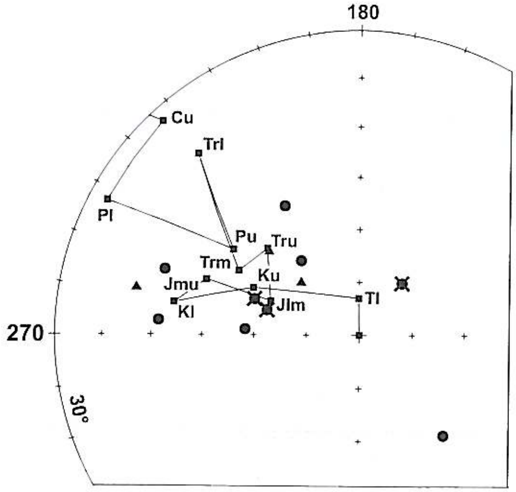

Fig. 3. Trias-Lias (circle) and Cenomanian (triangle) VGPs obtained in Morocco (Hailwood, 1975; Daly and Pozzi, 1976; Martin *et al.*, 1978; Westphal *et al.*, 1979) compared to the mean W Gondwana poles (square) from Van der Voo (1993). Poles used by Torcq *et al.* (1997) are highlighted by a cross.

mian (Autunian) data are available for Morocco and indicate paleolatitude of 2°N ± 3° (Morel *et al.*, 1984) which can be compared to the equatorial paleolatitude inferred for the Autunian of Southern France (Van der Voo, 1993).

Another constraint can be derived from Apulian data (Van der Voo, 1993, Muttoni *et al.*, 1996) which according to their coherency with the African plate should show a paleolatitude similar to that of Morocco (fig. 1). Consistent Apulian paleolatitudes of 7°N ± 4° (at Roma) for the Permo-Triassic boundary are again at odds with the Trias-Lias Moroccan data and the Pangea B configuration. In fact, as already mentioned in the introduction, the integration of Apulian data to compute the APWP of Gondwana (Muttoni *et al.*, 1996) results in a Pangea A2 configuration at the Permo-Triassic boundary.

Therefore, we conclude that the early Triassic Gondwana mean pole computed by Torcq *et al.* (1997) is biased by the Moroccan data of demonstrated late to post Triassic age (25% of the pole set), and that no support for the Pangea B relative paleolatitude prediction is found in the North African and Apulian Permian and early Triassic data. These areas being nearly equatorial, and thus weakly subjected to inclination error or octupole field effect, this is a quite strong argument against Pangea B. The only way to save Pangea B would be to assume that the shear zone between Laurussia and Gondwana was south of Morocco, that is Morocco (and Apulia) belonged to Laurussia during Pangea time. The geological consequences of this hypothesis should be investigated, but it seems clearly rejected by the Saharan craton data of Morel *et al.* (1984) and Henry *et al.* (1992).

4. The problem of age assignment

This question may be less important than the inclination error or NDF effect but it is in principle quite critical for the late Permian - Early Triassic reconstruction. Indeed if the 244 Ma pole of Gondwana is compared to the 214 instead of the 242 Ma Laurussia pole of Torcq *et al.* (1997), then Pangea A2 becomes acceptable.

The early Triassic age of all Gondwana sites, except the Permian Tanzania pole of Nyblade *et al.* (1993; used as a small circle), and the much younger Moroccan sites (early Lias or Cretaceous if remagnetized), seems to be supported by their biostratigraphy and the presence of reversals. On the other hand, several studies (5) used to compute the 242 Ma Laurussia pole are from the Kiaman reverse Permian superchron, including the Esterel study. So it seems that the age distribution of Gondwana and Laurussia poles used by Torcq *et al.* (1997) are biased toward late Trias (3 out of 13) and Kiaman (5 out of 19), respectively. This bias may be as great as the 30 Ma value mentioned above to accept Pangea A2. Indeed Menning (1995) placed the end of the Kiaman, Permian and Trias at about 265, 245 and 208 Ma, respectively. Recent Ar/Ar dates from Esterel (Zheng *et al.*, 1991-1992) give an age between 268 and 272 Ma for the Esterel volcanics, a much too old age for a pole used in the 242 ± 5 Ma mean Laurussia pole. Interestingly, the paleomagnetic age of the Esterel volcanics and intercalated sediments should be, according to the mean poles computed by Torcq *et al.* (1997), 235 and 255 Ma, respectively. Considering the quality of the Esterel data, this demonstrates an important age bias in the computed mean poles.

The above mentioned problems clearly point out that the paleomagnetic database must keep track of age reassessments through the progress of isotope chronology and biostratigraphy, particularly in pre Jurassic non marine formations. This is a very tedious task but unfortunately high quality paleomagnetic data are worthless if misdated.

5. Discussion and conclusions

Although the paleomagnetic data used to invoke an early Triassic Pangea B seem quite robust, we put forward an alternative interpretation of the latitudinal discrepancy between Laurussia and Gondwana, in terms of invalid paleomagnetic assumptions. Namely, the discrepancy can be solved by the combined effects of: 1) inclination error and/or non-dipole field on the south and north hemisphere location of Gondwana (except Apulia and Morocco) and Laurussia, respectively; 2) systematic age bias, and 3) use of the misdated and possibly remagnetized Moroccan sites. The fact that Apulian data fail to support early Triassic Pangea B is among the strongest arguments for (1). Although inclination error cannot be actually estimated in each redbeds formation studied, it is demonstrated in the Esterel and Argentina studies where volcanic rocks exhibit much larger inclination than sedimentary rock of the same age. As a late Triassic «Tethys twist» is highly unlikely in terms of geological record, energy balance and plate tectonics mechanisms (*e.g.*, Torcq *et al.*, 1997, estimated a minimum velocity of 9 cm/yr), our contention of systematic bias in the paleomagnetic database may be preferred. Whether Pangea B existed earlier and transformed into A2 in Permian times is discussed by Muttoni *et al.* (1996). However, the improvement on early Permian poles brought by B instead of A2 configuration is marginally significant. At that period the roughly EW oriented limit between Gondwana and Laurussia does not allow a distinction between B and A2 configurations. Whether the artifacts discussed here for late Permian - early Triassic also explain the remaining early Permian misfit of 9° ± 6° in the Pangea A2 configuration is beyond the scope of the present paper. Laurussian sites are more equatorial in early Permian but inclination error still largely affects the Gondwana sites.

Therefore, the Pangea B case is very probably a unique example of «constructive» addition of difference sources of error in paleomagnetic reconstructions, due to the hemispheric splitting of the two parts of Pangea and also the global northward movement during early Mesozoic. More generally, the above discussion should serve as a cautionary note in the systematic interpretation of paleomagnetically derived latitude discrepancies in terms of NS displacement, and in the uncritical confidence on tabulated paleopole ages. During review of the present paper, Van der Voo and Torsvik (2001) presented evidence for an octupole field of 10% in Permo-Triassic time and suggested that it accounts for the Pangea A misfit. However, they also show that a 20% octupole field is necessary to allow Pangea A (their fig. 7). So our contention is that a significant inclination error effect and age bias is added on top of non-dipole field.

Acknowledgements

We used for our discussion the GP database at dragon.ngu.no. Helpful comments were raised by H. Bertrand, K. Kodama, D. Kent, G. Muttoni and an anonymous reviewer during the several years of maturation of this work.

REFERENCES

ABOU-DEEB, J.M. and D.H. TARLING (1984): Upper Paleozoic paleomagnetic results from Algeria and Tunisia, *Tectonophysics*, **101**, 143-157.

ANSON, G.L. and K.P. KODAMA (1987): Compaction-induced inclination shallowing of the post-depositional remanent magnetization in a synthetic sediment, *Geophys. J. R. Astron. Soc.*, **88**, 673-692.

ARASON, P. and S. LEVI (1990): Compaction and inclination shallowing in deep sea sediments from the Pacific Ocean, *J. Geophys. Res.*, **95**, 4501-4510.

ARTHAUD, F. and P. MATTE (1977): Late Paleozoic strike-slip faulting in Southern Europe and Northern Africa: result of a right lateral shear zone between the Appalachians and the Urals, *Geol. Soc. Am. Bull.*, **88**, 1305-1320.

CHAUVIN, A., H. PERROUD and M.L. BAZHENOV (1996): Anomalous low paleomagnetic inclinations from Oligocene-lower Miocene red beds of the south-west Tien Shan, Central Asia, *Geophys. J. Int.*, **126**, 303-313.

COE, R.S., B.R. GLOBERMAN, P.W. PLUMLEY and G.A. THRUPP (1985): Paleomagnetic results from Alaska and their tectonic implications, in *Tectonostratigraphic Terranes of the Circum-Pacific Region*, edited by D.G. HOWELL, *Circum-Pacific Council for Energy and Mineral Resources*, vol. 1, 85-108.

COGNÉ, J.P., N. HALIM, Y. CHEN and V. COURTILLOT (1999): Resolving the problem of shallow magnetizations of Tertiary age in Asia: insight from paleomagnetic results from Qiangtang, Kunlun and Qaidam blocks (Tibet, China), *J. Geophys. Res.*, **104**, 17715-17734.

COLLOMBAT, H., P. ROCHETTE and D.V. KENT (1993): Detection and correction of inclination shallowing in deep sea sediments using the anisotropy of anhysteretic remanence, *Bull. Soc. Géol. France*, **164**, 103-111.

CREER, K., B.J. EMBLETON and D.A. VALENCIO (1970): Triassic and Permo-Triassic paleomagnetic data from South America, *Earth Planet. Sci. Lett.*, **8**, 173-178.

DALY, L. and J.P. POZZI (1976): Résultats paléomagnétiques du Permien inférieur et du Trias Marocain: comparaison avec les données africaines et sud-américaines, *Earth Planet. Sci. Lett.*, **29**, 71-80.

GARCES, M., J.M. PARES and L. CABRERA (1996): Further evidence for inclination shallowing in red beds, *Geophys. Res. Lett.*, **23**, 2065-2068.

HAILWOOD, E.A. (1975): The paleomagnetism of Triassic and Cretaceous rocks from Morocco, *Geophys. J.*, **41**, 219-235.

HALLAM, A. (1983): Supposed Permo-Triassic megashear between Laurasia and Gondwana, *Nature*, **301**, 499-502.

HENRY, B., N. MERABET, A. YELLES, M.M. DERDER and L. DALY (1992): Geodynamical implications of a Moscovian palaeomagnetic pole from the stable Sahara craton (Illizi basin, Algeria), *Tectonophysics*, **201**, 83-96.

HODYCH, J.P. and S. BIJASKANA (1993): Can remanence anisotropy detect paleomagnetic inclination shallowing due to compaction? A case study using Cretaceous deep sea limestones, *J. Geophys. Res.*, **98**, 22429-22441.

IRVING, E. (1977): Drift of the major continental blocks since the Devonian, *Nature*, **270**, 304-309.

JACKSON, M., S. BANERJEE and J. MARVIN (1991): Detrital remanence, inclination errors and anhysteretic remanence anisotropy: quantitative model and experimental results, *Geophys. J.*, **104**, 95-103.

KENT, D.V. and M.A. SMETHURST (1998): Shallow bias of paleomagnetic inclinations in the Paleozoic and Precambrian, *Earth Planet. Sci. Lett.*, **160**, 391-402.

KODAMA, K.P. and W. SUN (1992): Magnetic anistropy as a correction for compaction-caused paleomagnetic inclination shallowing, *Geophys. J. Int.*, **111**, 465-469.

KODAMA, K.P. and X. TAN (1997): Central Asian inclination anomalies: possible inclination shallowing in red beds?, *Eos, Trans. Am. Geophys. Un.*, **78**, F174.

KRUIVER, P.P., M.J. DEKKERS and C.G. LANGEREIS (2000): Secular variation in Permian red beds from Dôme de Barrot, SE France, *Earth Planet. Sci. Lett.*, **176**, 509-525.

LEFORT, J.P. and R. VAN DER VOO (1981): A kinematic model for the collision and complete suturing between Gondwanaland and Laurasia in the Carboniferous, *J. Geol.*, **89**, 537-550.

MARTIN, D.L., A.E.M. NAIRN, H.C. NOLTIMIER, M.H. PETTY and T.J. SCHMITT (1978): Paleozoic and Mesozoic paleomagnetic results from Morocco, *Tectonophysics*, **44**, 91-114.

MARZOLI, A., P.R. RENNE, E.M. PICIRILLO, M. ERNESTO, G. BELLIENI and A. DE MIN (1999): Extensive 200-million-year-old continental flood basalts of the Central Atlantic Magmatic Province, *Science*, **284**, 616-618.

MENNING, M. (1995): A numerical timescale for the Permian and Triassic periods: an integrated time analysis, in *The Permian of Northern Pangea*, edited by PERYT SCHOLLE and ULMER-SCHOLLE (Springer-Verlag), 77-97.

MOREL, P., E. IRVING, L. DALY and A. MOUSSINE-POUCHKINE (1984): Paleomagnetic results from Permian rocks of the Northern Saharan craton and motions of the Moroccan Meseta and Pangea, *Earth Planet. Sci. Lett.*, **55**, 65-74.

MUTTONI, G., D.V. KENT and J.E.T. CHANNEL (1996): Evolution of Pangea: paleomagnetic constraints from the Southern Alps, Italy, *Earth Planet. Sci. Lett.*, **140**, 97-112.

NYBLADE, A.A., Y. LEI, P.N. SHIVE and A. TESHA (1993): Paleomagnetism of Permian sedimentary rocks from Tanzania and the Permian paleogeography of Pangea, *Earth Planet. Sci. Lett.*, **118**, 181-194.

QUIDELLEUR, X., J.P. VALET, V. COURTILLOT and G. HULOT (1994): Long term geometry of the geomagnetic field for the last 5 Myr: an updated secular variation database from volcanic sequences, *Geophys. Res. Lett.*, **21**,1639-1642.

ROCHETTE, P., F. BEN ATIG, H. COLLOMBAT, D. VANDAMME and P. VLAG (1997): Low paleosecular variation at the equator, a pilgrimage from Galapagos to Esterel with A. Cox and H. Zijderveld, *Geol. Mijnbouw*, **76**, 9-19.

ROCHETTE, P., E. TAMRAT, G. FÉRAUD, R. PIK, V. COURTILLOT, E. KETEFO, C. COULON, C. HOFFMANN, D. VANDAMME and G. YIRGU (1998): Magnetostratigraphy and timing of the Oligocene Ethiopian traps, *Earth Planet. Sci. Lett.*, **164**, 497-510.

ROSLER, W., W. METZLER and E. APPEL (1997): Neogene magnetic polarity stratigraphy of some fluviatile Siwalik sections, Nepal, *Geophys. J. Int.*, **130**, 89-111.

SCHNEIDER, D.A. and D.V. KENT (1990): The time averaged paleomagnetic field, *Rev. Geophys.*, **18**, 71-96.

SEBAI, A., G. FÉRAUD, H. BERTRAND and J. HANES (1991): ^{40}Ar/^{39}Ar dating and geochemistry of tholeitic magmatism related to the early opening of the Central Atlantic rift, *Earth Planet. Sci. Lett.*, **104**, 455-472.

SMITH, A.G. and R.A. LIVERMORE (1991): Pangea in Permian to Jurassic time, *Tectonophysics*, **187**, 135-179.

TAUXE, L. and D.V. KENT (1984): Properties of detrital remanence carried by hematite from study of modern river deposits and laboratory redeposition experiments, *Geophys. J. R. Astron. Soc.*, **76**, 543-561.

TORCQ, F., J. BESSE, D. VASLET, J. MARCOUX, L.E. RICOU, M. HALAWANI and M. BASAHEL (1997): Paleomagnetic results from Saudi Arabia and the Permo-Triassic Pangea configuration, *Earth Planet. Sci. Lett.*, **148**, 553-567.

VAN DER VOO, R. (1993): *Paleomagnetism of the Atlantic Thetys and Iapetus Oceans* (Cambridge Univ. Press, Cambridge), pp. 411.

VAN DER VOO, R. and T. H. TORSVIK (2001): Evidence for late Paleozoic and Mesozoic non-dipole fields provides an explanation for the Pangea reconstruction problems, *Earth Planet. Sci. Lett.*, **187**, 71-81.

VAUCHEZ, A., S.F. KESSLER, J.P. LÉCORCHÉ and M. VILLENEUVE (1987): Southward extrusion tectonics during the Carboniferous Africa - North America collision, *Tectonophysics*, **142**, 317-322.

VLAG, P., D. VANDAMME, P. ROCHETTE and K. SPINELLI (1997): Paleomagnetism in the Esterel rocks: a revisit 22 years after the thesis of H. Zijderveld, *Geol. Mijnbouw*, **76**, 21-33.

WESTPHAL, M., R. MONTIGNY, R. THUIZAT, C. BARDON, A. BOSSERT, R. HAMZEH and J.P. ROLLEY (1979): Paléomagnetisme et datation du volcanisme permien, triasique et crétacé du Maroc, *Canad. J. Earth Sci.*, **16**, 2150-2164.

YANG, Z., M.G. MOREAU, H. BUCHER, J.-L. DOMMERGUES and A. TROUILLER (1996): Hettangian and Sinemurian magnetostratigraphy from Paris Basin, *J. Geophys. Res.*, **101**, 8025-8042.

ZHENG, J.S., J.F. MERMET, N. TOUTIN-MORIN, J. HANES, A. GONDOLO, R. MORIN and G. FÉRAUD (1991-1992): Datation ^{39}Ar-^{40}Ar du volcanisme permien et de filons minéralisés en Provence orientale, *Geodyn. Acta*, **5**, 203-215.

ZIJDERVELD, J.D.A. (1975): Paleomagnetism of the Esterel rocks, *Ph.D. Thesis*, Utrecht University, pp. 199.

(received April 26, 2001;
accepted June 22, 2001)